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Estimation of lateral hydrothermal flow distance from spatial variations in oceanic heat flow

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Abstract. Measured heat flow in young oceanic crust is generally less than predicted by lithospheric cooling models, even where thick sediments had been expected to isolate the crust from the ocean and hence eliminate hydrothermal heat transfer. At isolated sites with basement outcrops or topographic highs, however, heat flow sometimes exceeds the model predictions. It thus appears that water migrates and upwells at distant sites, hence transferring heat laterally. Simple estimates of the lateral flow distance can be made when heat flow data have adequate areal sampling. The data can be parametrized by distance from the presumed upwelling site, and integrated to estimate the area from which heat must be transferred. Along the Juan de Fuca ridge, the minimum effective lateral flow distances are 8 km for 3-5 Ma crust, and 2 km for younger (< 1 Ma) crust.

Introduction

Several lines of evidence suggest that sea water can flow laterally for distances of kilometers through young oceanic crust. Although this flow is difficult to measure directly, various indirect approaches yield a similar view.

One approach uses the discrepancy between the conductive heat flow measured at the sea floor and the higher values predicted by thermal models of the cooling lithosphere to infer the heat transfer by hydrothermal flow. Assuming the models are reasonably accurate, the missing heat is attributed to advective heat transfer by water flow, and so must appear somewhere, either as high conductive heat flow elsewhere or as advective discharge to the sea. Analyses of global heat flow data [*Stein and Stein*, 1994; *Stein et al.*, 1995] find that this discrepancy persists to crustal ages of about 65 Ma, even for igneous crust overlain by thick sediments. This result is at first surprising, given the earlier view that about 100-200 m of sediment would be sufficiently impermeable to seal off the crust from the sea, such that heat flow at heavily sedimented sites would yield a "reliable" value, i.e. that predicted by a thermal model without hydrothermal flow [e.g., *Anderson and Hobart*, 1976; *Sclater et al.*, 1976]. The simplest way to reconcile the observations with the traditional ideas is to assume that if at a particular site water cannot flow vertically through thick hydraulically non-conductive sediments, it flows laterally to a fault or basement outcrop, and then is manifested as either high conductive heat flow or hot water exiting to the sea [*Stein and Stein*, 1994]. It thus appears that lateral water flow, previously inferred for specific sites [e.g., *Becker and Von Herzen*, 1983; *Langseth et al.*, 1992], is a common phenomenon.

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A similar view emerges from hydrologic modeling. Measured sediment properties imply that 50-200 m of sediment would be hydraulically non-conductive [*Karato and Becker*, 1983; *Snelgrove and Forster*, 1996]. Modeling also indicates that water can flow for considerable distances in the upper few hundred meters of igneous crust, which is known from drilling to be highly permeable [e.g., *Fisher et al.*, 1994; *Fisher and Becker*, 1995]. This view is supported by the observation that for the FlankFlux area (discussed shortly) heat flow varies inversely with depth to basement rock, suggesting that the basement is maintained as an essentially isothermal surface by fluid flow near its top [*Davis et al.*, 1989].

A third line of evidence is provided by geochemistry, via analysis of the interactions between seawater, sediment, and crustal rock [e.g., *Elderfield and Schultz*, 1996]. From isotopic ratios in sediment, *Baker et al.* [1991] proposed that large-scale lateral advection of seawater takes place in the oceanic crust in an area of the central Pacific. Direct evidence for lateral flow is provided by chemical variations in basement fluids along the flank of the Juan de Fuca Ridge [*Elderfield et al.*, 1996].

These observations motivated us to see whether heat flow data, which qualitatively suggest that water flows laterally for long distances, can also provide quantitative constraints on the lateral extent of water flow. It turns out that simple constraints can be derived using data from densely sampled (kilometer or closer spacing) heat flow surveys, which are detailed enough to show both the two-dimensional spatial complexities of the heat flow field and its broad regional features.

Data

Figure 1 shows results of two such surveys. The upper panel shows data from the FlankFlux survey of 3-5 Ma crust east of the Juan de Fuca ridge [*Davis et al.*, 1992]. Several points emerge from comparison of the data to the predictions of two thermal models, one without hydrothermal cooling (GDH1) [*Stein and Stein*, 1992], and one with hydrothermal cooling (CYH1). Heat flow varies with basement relief, being highest over basement highs termed "penetrators" [*Davis et al.*, 1989]. Except near these highs, heat flow is generally less than predicted by GDH1, implying that much of the heat is transported by hydrothermal flow. The discrepancy is essentially the same for other proposed thermal models without hydrothermal cooling, because at such young ages different models make similar predictions [*Stein and Stein*, 1994]. In contrast, heat flow above the basement highs exceeds the GDH1 predictions, and thus the conductive heat flow expected in the absence of hydrothermal flow, implying lateral heat transfer by hydrothermal flow. Similarly, 0-1 Ma crust in Middle Valley, a sediment-covered area close to the Juan de Fuca Ridge, shows isolated areas of high heat flow surrounded by sites with heat

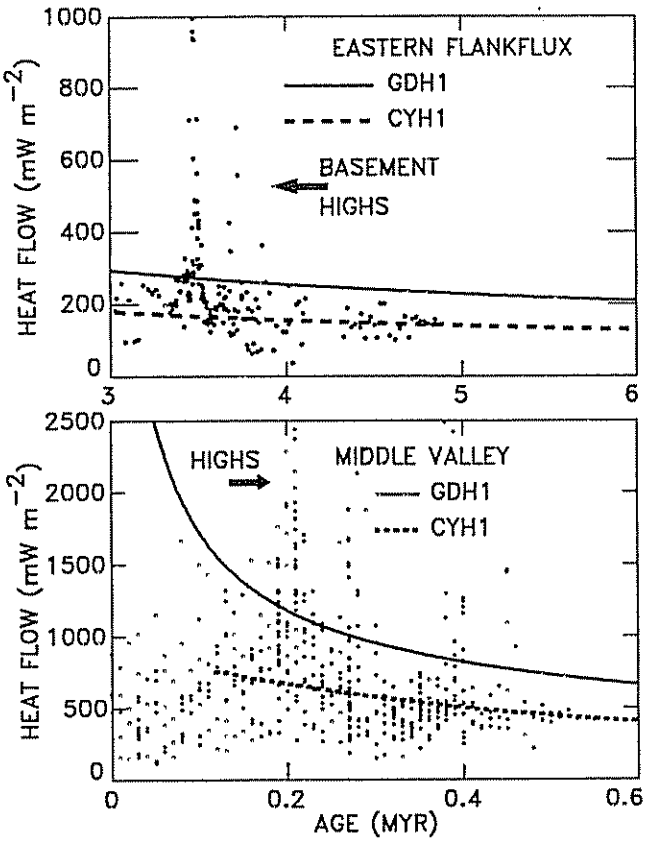

Fig. 1. Heat flow data from two densely sampled surveys of generally well sedimented young lithosphere. Most values are significantly lower than predicted by the GDH1 model, which includes no hydrothermal cooling, suggesting that hydrothermal heat transfer is pervasive. Values exceeding those predicted typically occur over basement or topographic highs. Also shown are predictions of the CYH1 model for average heat flow versus age including the effects of hydrothermal cooling. For graphic purposes, a few of the highest values are not shown.

Model

These data permit simple estimates of the range of lateral water flow. As previously noted [*Lonsdale and Becker*, 1985; *Fisher and Becker*, 1991], average heat flow decays with distance from high value sites, such as penetrators. We describe this variation using a simple parameterization of the heat flow fraction (HFF) by the radial distance (x) from the nearest penetrator, $HFF(x) = ax^{-b}$ (Figure 3). Thus the areally averaged heat flow fraction to a distance r is

$$\overline{HFF}(r) = \frac{1}{\pi r^2}\int_0^r ax^{-b}\, 2\pi x\, dx = \left(\frac{2a}{2-b}\right) r^{-b}$$

which is well behaved for $b \leq 2$. To estimate the lateral water flow distance, we find the radius r_1 over which the areally averaged heat flow fraction is one ($\overline{HFF}(r_1) = 1$),

$$r_1 = (2a/(2-b))^{1/b}$$

such that excess conductive heat flow at the penetrator is supplied by lateral water flow moving the missing conductive heat flow from elsewhere.

r_1 characterizes a presumed average radial water flow on a large (perhaps kilometer) scale, rather than finer-scale flow structure. In this formulation, r_1 is a lower bound on the effective lateral water flow distance - water may come from flow fractions less than one [*Davis and Villinger*, 1992; *Fisher et al.*, 1997].

Both the high and low heat flow values provide useful information. Low values support the observation that even in well-sedimented (more than 100 m sediment) areas, conductive heat flow is significantly less than predicted. This discrepancy is reasonably well described by the CYH1 model, in which we estimated near-ridge hydrothermal cooling from observations that both magma chambers inferred from seismic imaging and earthquakes occur deeper than expected for a thermal model without hydrothermal cooling [*Pelayo et al.*, 1994; *Stein et al.*, 1995]. CYH1 (for Composite Young Hydrothermal) predicts areally averaged heat flow for young ages. The good fit to the dense survey data is gratifying, as CYH1 makes pure predictions, because it was derived without heat flow data for ages less than 10 Myr.

The high values, in contrast, show where water is presumably going and how much heat it transfers. Figure 2 shows the spatial distribution of the heat flow fraction, the ratio of the observed value to that predicted by the model (GDH1) without hydrothermal cooling. Broad regions of low heat flow border localized sites of high heat flow, implying that water moves heat from sites with low heat flow to sites with high heat flow.

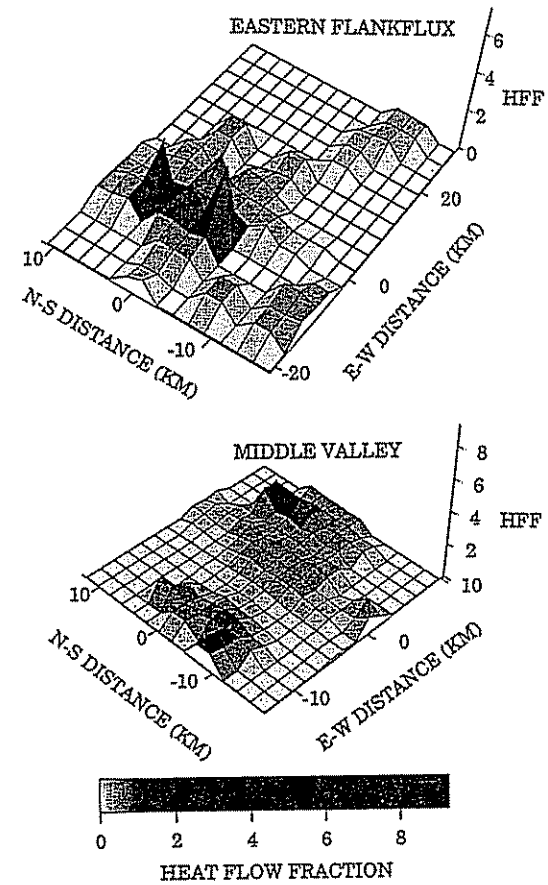

Fig. 2. Smoothed surface plot of heat flow data for the eastern portion of the FlankFlux area (top) and Middle Valley (bottom). Data are shown as heat flow fraction, the ratio of the observed value to that predicted by a model without hydrothermal cooling. Except near basement highs, most measurements have heat flow fractions less than one, indicating significant lateral heat transport by hydrothermal flow.

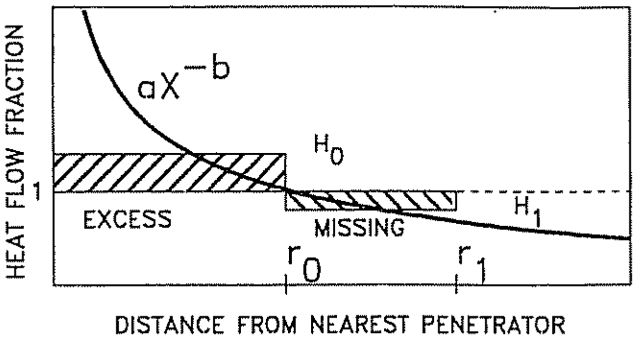

Fig. 3. Parameterization of heat flow fraction as a function of radial distance (x) from nearest penetrator or other heat flow site. The minimum effective lateral flow distance r_1 is estimated assuming that excess heat flow near the penetrator is supplied by missing heat flow out to r_1. Areally averaged heat flow is H_0 to the radius r_0 where the heat flow fraction is one, and H_1 from radius r_0 to r_1. Shaded areas are not equal due to the radial area weighting, but are equal once weighted.

further away, but must on average come at least this far to supply the high heat flow at the penetrator. To see this, consider a further simplification in which the areally averaged heat flow is H_0 to the radius r_0 where the heat flow fraction is one, and H_1 from radius r_0 to r_1 (Figure 3). Because the areally averaged heat flow fraction is one out to r_1,

$$H_0 \pi r_0^2 + H_1 \pi (r_1^2 - r_0^2) = \pi r_1^2$$

$$r_1^2 = r_0^2 \ (H_0 - H_1)/(1 - H_1) .$$

If a significant quantity of heat is transferred advectively at the seafloor by vertical water flow at penetrators or other basement features, even the high conductive heat flow values do not fully reflect the heat transported laterally by water flow. Thus the high measured H_0 underestimates the excess heat flow, and a larger radius than calculated is required to supply it. In general, the relation of the effective minimum flow distance to the detailed water flow depends on the flow geometry. Moreover, real hydrothermal fields have flow geometries more complex than simple radial flow. Nonetheless, it is interesting to compare real data to the simple model.

For FlankFlux (Figure 4, top), the best fit values to the data averaged in 2-km bins are $a = 1.8 \pm 0.3$ and $b = 0.37 \pm 0.06$ Thus $r_1 = 8 \pm 4$ km is the minimum effective lateral water flow distance. The areally averaged heat flow fraction depends on the distance r assumed. It is 0.63 to a distance of 30 km (maximum range of the data), 0.73 to 20 km, and 0.94 to 10 km. Hence if such penetrators are on average about 8 km apart, they could account for all the heat flow discrepancy. If, however, such features are spaced significantly further apart, there are probably other outlets for water flow.

At Middle Valley, the heat flow fraction appears to vary radially with distance from the highs (Figure 4, bottom), declining till about 10 km, and then starting to rise, perhaps due to more distant features. A fit to the points within 10 km in 1-km bins yields $a = 1.04 \pm 0.2$, $b = 0.67 \pm 0.13$, and $r_1 = 2 \pm 0.6$ km. The areally averaged heat flow fraction is 0.33 to a distance of 10 km. Thus features approximately 2 km apart are needed to account for all the heat flow discrepancy. If such features are significantly further apart, there are probably other outlets for water flow.

Discussion

These examples show that areally distributed heat flow data can be used to estimate a minimum effective water flow distance and the areally averaged heat flow fraction. The available data are sufficient both to illustrate what can be done, and to suggest the utility of even better areal sampling.

The difference in the minimum effective lateral flow distance between the two areas seems plausible. At Middle Valley, the heat flow highs are closer spaced than at FlankFlux. More generally, the spacing between heat flow highs should reflect both the basement topography and sediment thickness, governing where basement highs approach the sea floor. Thus in general younger areas should have closer spaced heat flow highs and thus smaller average flow distances.

As Figure 2 shows, present data give a sense of the two-dimensional variation in heat flow, but do not fully resolve it. It is unclear whether unsampled heat flow highs transport a significant fraction of the missing heat flow. Thus areal analyses like those presented here offer insight into key issues, but cannot yet resolve them.

For example, what significance can be ascribed to the heat flow fraction remaining less than one for distances significantly beyond the estimated minimum effective flow radius (or equivalently, that the areally averaged heat flow is less than one)? We see four possible contributing factors. First, some penetrators or other discrete heat flow highs may not have been sampled. These highs need not be topographic or basement features; for example, faults might provide high-permeability paths for fluid flow [*Williams et al.*, 1974]. Second, some of the missing heat is transferred by water flow at the heat flow highs [*Fisher et al.*, 1997; *Wheat et al.*, 1997], so the measured high

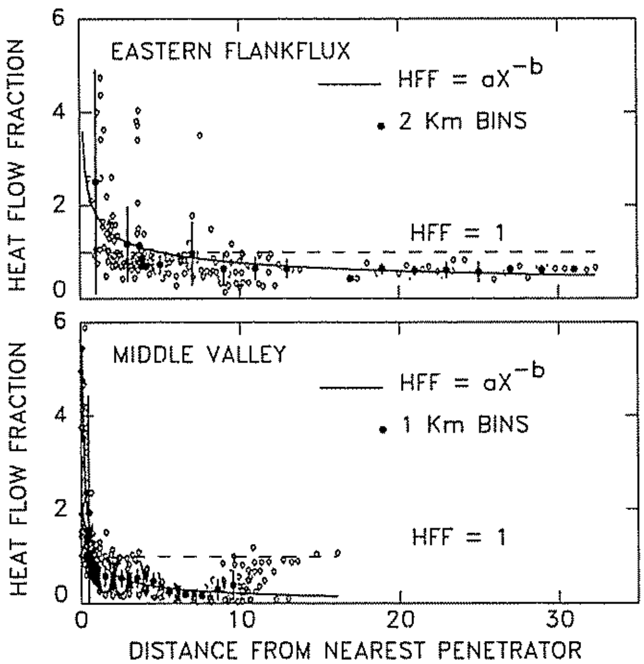

Fig. 4. Heat flow fraction as a function of radial distance from the nearest penetrator or other heat flow high for FlankFlux and Middle Valley data. Data (diamonds) are binned (solid circles), and a best fit curve is fit. The zone of high heat flow is greater at FlankFlux than for Middle Valley, implying a larger minimum effective lateral flow distance, and the heat flow fraction away from penetrators is higher at FlankFlux. For graphic purposes, a few values are not shown.

conductive heat flow underestimates the true value. Third, some of the missing heat may be transported by diffuse vertical flow through the sediment, although heat flow measurements suggest that few sites have water flow sufficient to transport significant amounts of heat. Fourth, the thermal models may systematically predict too high a heat flow.

These factors, and crustal age, may contribute to the apparent difference in heat flow fraction as a function of distance between the different areas. Figure 4 shows both sites on the same distance scale, emphasizing two points. First, the zone over which high heat flow extends is greater at FlankFlux than for Middle Valley, implying a larger minimum lateral flow distance. Second, the heat flow fraction away from the penetrators is higher at FlankFlux. Thus there is an apparent difference between the areally averaged heat flow fractions: about 2/3 for FlankFlux and 1/3 for Middle Valley. To decide if the difference is meaningful, we would have to be confident that all basement highs or other sites with high heat flow had been sampled. If so, and the heat flow fraction remained significantly less than one for a greater distance than the estimated minimum average flow, or equivalently the areally averaged heat flow remained less than one, we could exclude the possibility that net conductive heat transfer less than predicted reflects missed heat flow highs, and focus on other possible contributing factors. Hence as better-sampled data at more sites become available, it will make sense to refine the simple approach taken here to explore some of these issues.

In summary, simple analysis of the spatial variation in heat flow can yield interesting insight into the lateral extent of hydrothermal flow in oceanic crust. Certainly neither this approach, nor any other, can alone fully resolve the complexities of the flow. The approach here requires a simple average spatial pattern of high heat flow decaying smoothly with distance. Hence this analysis does not do well for the Galapagos area, where the pattern is more complicated, in part due to incomplete sediment cover [*Green et al.*, 1981]. It seems likely, however, that this approach together with flow modeling and geochemical analyses will be useful. It will be interesting to compare the results of different analyses, because each may place constraints on the other. We expect these approaches will bear fruition as better-sampled data and improved analysis techniques become available.

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